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Energy-efficient envelope design for high-rise apartments

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Abstract

The energy required to create a comfortable living environment in high-density cities in hot and humid climates usually demands a substantial electricity usage with an associated environmental burden. This paper describes an integrated passive design approach to reduce the cooling requirement for high-rise apartments through an improved building envelope design. The results show that a saving of 31.4% in annual required cooling energy and 36.8% in the peak cooling load for the BASECASE apartment can be achieved with this approach. However, all the passive strategies have marginal effect on latent cooling load, often less than 1%.

Keywords: High-rise apartments; Hong Kong; BASECASE model; TRNSYS; Envelope design; Thermal simulation; Green architecture; Energy efficient building

1. Introduction

The rapid economic development and the high population densities of many Southeast Asian countries and China have created a number of cities dominated by high-rise apartment buildings. Hong Kong is one of the most well-known examples of this type of city. About 90% of its total population live in high-rise buildings and half of these are in densely built-up public housing estates [1]. The increase in electricity consumption by the residential sector, particularly in the summer months, has been caused by the growing demand for air-conditioning systems to provide thermal comfort for the occupants [2]. The ownership of air-conditioners has risen from 50% in 1989 to 90% per household in 1993 [3]. This phenomenon suggests that there is a potential to reduce the energy consumption and resultant greenhouse gas emissions by reducing the need for air-conditioning in apartment buildings. Local building designers have largely ignored passive design strategies, which can moderate internal temperatures and hence reduce building energy consumption by adjusting the building to match the local climatic forces. Most previous passive design studies have focused on houses and commercial buildings in moderate, cold or hot arid climates.

This paper describes an investigation of the effect of six passive design strategies, namely, insulation, thermal mass, glazing type, window size, colour of external wall and external shading devices, on both the annual required cooling energy and peak cooling load on a high-rise apartment building in Hong Kong. This study quantifies the energy savings and improvement in human comfort if these passive strategies are integrated into such buildings. The paper begins with a general overview of the climate in Hong Kong and then reviews previous research into the use of passive design strategies on high-rise buildings in this climate. The model used to simulate the strategies is then described, followed by the results and conclusions of the investigation.

2. Climatic conditions in Hong Kong

Hong Kong is located at the latitude 22° 18′ N and longitude 114° 10′ E, and he climate is classified as sub-tropical. In the winter months (November–February), the mean temperature is approximately 15–18 °C. According to the Hong Kong Observatory [4], it is not uncommon for temperatures to drop below 10 °C in urban areas, and the lowest temperature recorded at the Observatory is 0 °C, although sub-zero temperatures and frost occur at times on high ground and in the new territories. The spring season is short, humid and sometimes very foggy. The temperature also tends to fluctuate widely from day to day. In the summer months, between May and September, the weather is mainly tropical, i.e. hot and humid with occasional showers or thunderstorms. Afternoon temperatures frequently exceed 32 °C between June and September, with the mean temperature around 27–29 °C. The autumn season is short and lasts only

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from mid-September to early November. The mean annual rainfall is about 2225 mm of which 80% falls between May and September. The hot and humid long summer season of Hong Kong creates a huge demand for air-conditioning for comfort cooling.

3. Previous research

There is only a limited amount of research literature on energy-efficient apartment building design in hot and humid climates. Most of the literature in the Southeast Asian region has focused on comfort conditions for building occupants [5,6], while the majority of apartment design-related studies have been conducted in Hong Kong. Lam [7] reported a study in 1993, which investigated the impact of glazing type, external shading and wall insulation on energy consumption. However, the apartment size studied was too large (160 m^2) compared to the majority of current apartments in Hong Kong (55 m^2). In the model used, the layout of floor plan is oversimplified, the living room window is too large and no window is provided in the kitchen, bathroom or laundry. The other shortfall is that only north- and south-facing windows are included in the model, which does not correspond with the majority of eight flat-per-floor designs currently seen in Hong Kong. Lam's study also did not consider the possibility of natural ventilation. Higgs [8] reported another study in 1994, which investigated the effects of self-shading on the cooling load and energy consumption. This study showed that self-shading reduced both the peak cooling load and energy consumption of south- and west-facing apartments by more than 15%. However, this study did not incorporate any occupancy schedule or internal loads for the flats and assumed that all rooms were conditioned continuously. This assumption is likely to distort the result and hence reduce the validity of this study. Another study [3] in 2000 focused on the electricity consumption and the current design of high-rise residential buildings. It contained valuable information of the various design characteristics of high-rise apartment buildings, which has been used in the present study. The paper also predicted the energy saving by introducing 25 mm insulation and replacing all windows with tinted glass. Unfortunately, the area of the apartments and the occupancy schedules were not reported and therefore the applicability of the results is limited.

Bojic et al. [9] investigated the influence of wall insulation thickness and its position in the building envelope on peak cooling load and energy consumption. The study showed that cooling energy consumption could be reduced by approximately 7% by placing thermal insulation on the outside of the envelope walls. Although this study provided detailed results on the relationship between thickness and position of thermal insulation in the envelope wall, it only studied south-facing apartments. The operating schedule of plug loads in kitchen also limited the applicability of the study. The schedule used a 518 W/m^2 plug load in the kitchen between the hours 21:00 and 00:00, although the kitchen was deemed to be unoccupied at the time with no lights were switched on.

In a subsequent study by Bojic et al. [10], the same thermal model was used to evaluate the influence of insulation in internal partitions. The results indicated that there is a substantial energy-saving potential when insulation is used in the partition wall between the kitchen and the living room, but this again indicated that perhaps an unrealistic heating load had been assumed for the kitchen. The same authors later investigated the effects of the shading coefficient of windows on peak cooling load and energy consumption using the same building model [11]. This study reported the effect of orientation on energy consumption. Only a generic glazing type was investigated in which the only variable is the shading coefficient. In reality, the shading coefficient is not the only property of a glazing system that affects the indoor climate. The thermal transmittance and thermal capacitance are also influential properties, especially when the flats are occupied at night and where solar gain through windows only occurs during a minor part of the occupied hours.

Generally speaking, previous studies have focused only on a particular envelope component in a generic building. There is a lack of comparative study of the relative efficiency and impact of passive design strategies. However, the above studies provided resources for this research, such as input parameters and benchmarks for validations that are hard to obtain otherwise. The authors of the present study have previously investigated the effect of five low-energy building envelope design strategies, namely, wall insulation, glazing type, colour of external wall, window size and external shading, using the software ENERGY-10 [12]. The results indicated that up to 40% of annual required cooling energy could be saved. This study, however, also had some limitations. Firstly, the software used could not simulate the effect of natural ventilation during unoccupied hours. Secondly, the software could only simulate two thermal zones and thus the model was only able to simulate a living/dining and a bedroom zone. This arrangement ignored any inter-zonal thermal exchange, and the influence of the bathroom and kitchen. Finally, only a west-facing apartment was modelled and the energy saving achieved by each individual strategy was calculated, rather than assessing an integrated design, which combined the effects of all strategies.

4. The BASECASE model

The objective of the present investigation is to overcome the limitations of previous studies, and detailed building energy simulations have been carried out using the computer program TRNSYS [13]. A BASECASE building model of a representative building design was developed. It was decided to select a current building design used in Hong Kong as the BASECASE, rather than creating a generic design. The public rental flats being developed by the housing au-

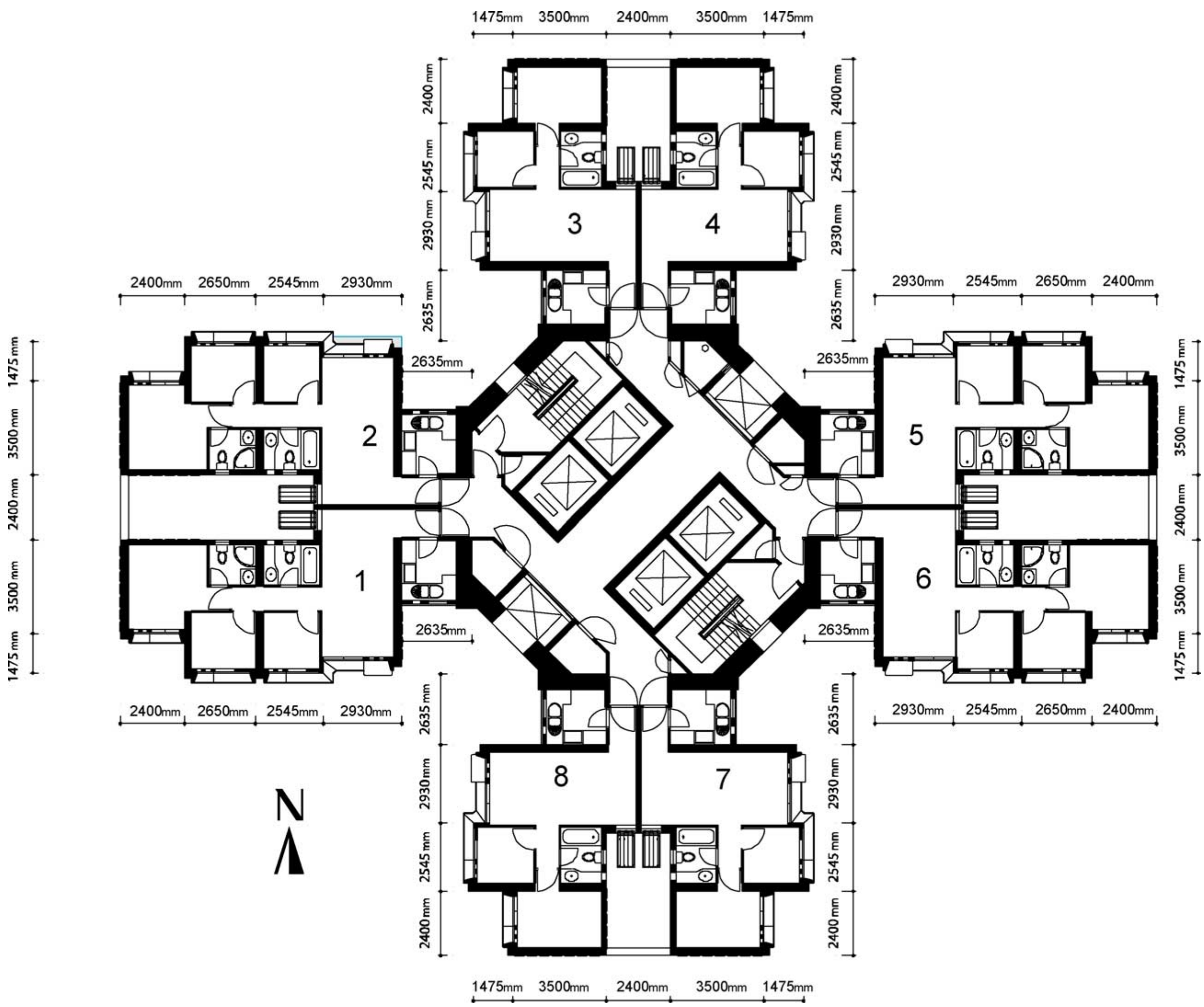

Fig. 1. Typical floor plan of Concord Block (source: HKHA, 2001).

thority use a standardized design of Concord Blocks, which is representative of the high-rise public apartments to be constructed in the near future. Concord Blocks are also similar to the current designs used by the private sector [3]. A Concord Block is a forty-two storey apartment building with eight flats per floor (Fig. 1). Since this is a standard floor plan for various housing estates developed by the Hong Kong Housing Authority (HKHA), there is no fixed location or orientation. Area and volumes of the rooms in two- and three-bedroom flats in a Concord Block are shown in Table 1.

4.1. BASECASE model parameters

The external walls of the BASECASE model are each composed of three layers: a medium colour wall tile on a cement/sand plaster layer on the outdoor side, a 150 mm thick reinforced concrete layer and a 13 mm thick gypsum

Table 1
Area and volume of rooms in two- and three-bedroom flats in a Concord Block

	Three-bedroom flats (flats 1, 2, 5, 6)		Two-bedroom flats (flats 3, 4, 7, 8)	
	Area (m^2)	Volume (m^3)	Area (m^2)	Volume (m^3)
Bedrooms 1 and 2	16.5	43.1	13.8	38.5
Study room	5.1	14.2	n.a.	n.a.
Living room	21.4	60.0	19.6	54.9
Bathroom(s)	6.9	19.3	3.8	10.5
Kitchen	5.2	14.5	5.2	14.5

n.a.: indicates “not applicable” since there is no study in a two-bedroom flat.

Table 2
Characteristics of building materials used in BASECASE model

Material	Density (kg/m^3)	Specific heat (J/kg K)	Thermal conductivity (W/m K)
Concrete	2400	653	2.16
Cement/sand plaster	1860	840	0.72
Gypsum plaster	1120	837	0.38

plaster layer with emulsion paint on the indoor side. The overall U-value of the external wall is 2.86 W/m^2 K. The indoor partition walls are each composed of three layers: a 100 mm thick concrete layer covered with two 13 mm gypsum plaster layers with emulsion paint, with an overall U-value of 3.11 W/m^2 K. The living room and bedrooms are finished with a vinyl tile or timber flooring; the bathrooms and kitchens are finished with quarry tiles. The floor slab is 300 mm thick reinforced concrete. The ceiling finish is 13 mm thick gypsum plaster with emulsion paint. The ceiling and floor were assumed to be adjacent to flats with equivalent thermal conditions and hence there would be no thermal exchange with these zones. The properties of the various materials used in these apartments are summarized in Table 2. The windows all use a single pane of 5 mm thick clear glass with a visible transmittance of 0.9 and aluminium frames resulting in shading and solar heat gain coefficients (SHGC) of 0.97 and 0.83, respectively, and a U-value of 5.82 W/m^2.

The HVAC systems for the BASECASE model are assumed to be window-mounted direct expansion air-conditioners with a typical coefficient of performance (COP) of 2.5 [14]. Only the living room, bedrooms and the study room are conditioned with a set point of 24 °C. The power densities of the lighting systems are 10 W/m^2 for the bathroom, 20 W/m^2 for the living room, 17 W/m^2 for the kitchen, bedrooms and study room. The living room has a plug load of 28 W/m^2 during occupied hours and 1.4 W/m^2 during unoccupied hours, while the bedrooms have a plug load of 24 W/m^2 during occupied hours. The kitchen has a plug load of 25.9 W/m^2, but an extra load of 493 W/m^2 is assumed for the gas stove during cooking hours. The bathrooms have no plug loads.

The apartments are occupied typically by three to four people from 19:00 to 07:00 hours next morning. The living room is occupied from 19:00 to 23:00 hours. Bedrooms are occupied from 21:00 to 07:00 hours. The kitchen is occupied from 19:00 to 20:00 and 06:30 to 07:00 hours. Windows are assumed to be open when the ambient temperature is above 22 °C with an air change rate of 11.5 ACH during unoccupied hours. Otherwise, windows are assumed to be partially open with an air change rate of 2.5 ACH during unoccupied hours. Windows are always shut whenever the air-conditioners are operational. This ventilation algorithm is based on the authors' own experience that a closed building on hot days would result in an overheated space during the early occupied hours of the evening. Air infiltration is calculated using a subroutine within the TRNSYS program (Type 571) based on equations from ASHRAE.

4.2. Verification of BASECASE model

Using the parameters described above, the performance of BASECASE building was simulated using the 1989 weather data file from the local meteorological observatory as the climatic data input. This is regarded as a typical representation of the weather for Hong Kong [15]. The effects of inter-block shading and self-shading were ignored [16]. The model, which consisted of both two- and three-bedrooms flats, was simulated in eight orientations by rotating the model in steps of 45°. The results (Fig. 2) varied with different flat sizes and orientations. They ranged from 102.1 kWh/m^2 for a north-facing two -bedroom flat to 121.5 kWh/m^2 for a west-facing three-bedroom flat. The average annual required cooling energy per total floor area of apartment was predicted to be 111 kWh/m^2 (Fig. 2). This figure is within 8% or 7 kWh/m^2 per annum of published survey data [17]. The predictions of the BASECASE model were found to correlate well with the figure of 93.8 kWh/m^2 from a more recent simulation study by Bojic et al. [9]. Even though the flat sizes are 10% larger than in the Concord Block, the models' predictions are within 3.5% of each other.

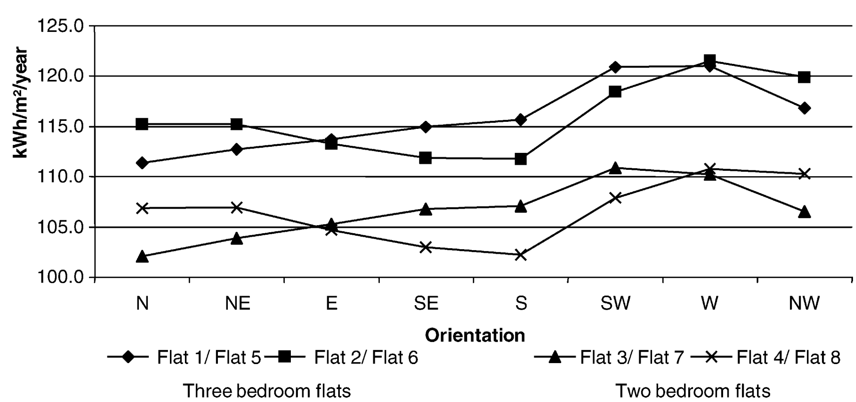

Fig. 2. Annual required cooling energy per net conditioned floor area of flats 1–8 for different orientations.

5. Results and discussion

In this paper, the effects of the various low-energy design strategies on the cooling load are evaluated for the whole apartment. Two variables were selected to represent the cooling load, namely annual required cooling energy and peak cooling load. Annual required cooling energy is defined as the output from the cooling system rather than the actual amount of energy consumed by the cooling system. Peak cooling load is defined as the maximum amount of heat that needs to be removed from the conditioned space in any single hour over the year in order to maintain the set point temperature. For each low-energy design strategy, the analysis indicates the change in both the required cooling energy and the peak cooling load of the modified apartment against the BASECASE apartment.

Six passive thermal design strategies were identified, namely, insulation, thermal mass, colour of external walls, glazing systems, window size and shading devices. As previous, the BASECASE flat was assumed to be fully air-conditioned (24 °C db and 50% rh) during the occupied hours with no outside fresh air supply. The latent load is ignored in this study since the selected envelope designs will not have a significant effect on the moisture content of the space except when the indoor dry bulb temperature drops below the dew point temperature, which rarely happens in the hot summer climate of Hong Kong.

5.1. Insulation and thermal mass

Different levels of thermal resistance can be achieved by adding extruded polystyrene (EPS) thermal insulation to the external walls of the BASECASE apartment. The thickness of EPS was increased in steps of 25 mm to a maximum thickness of 100 mm. The maximum thickness was determined by the maximum total wall thickness of 300 mm (100 mm insulation plus 200 mm reinforced concrete wall slab) that can be exempted from the gross floor area (GFA) calculation, as stipulated by the Joint Practice Note No. 2 [18]. The effect of thermal capacitance is simulated by putting the insulation on the inside surface, in the middle or on the outside surface of the reinforced concrete wall slab.

The introduction of 100 mm thick insulation on the inside of the wall produces the maximum saving of 19.4% in annual required cooling energy when compared to the BASECASE (Fig. 3). The maximum reduction of 29.2% in peak cooling load was obtained when 100 mm thick insulation was placed on the outside of the external wall (Fig. 4). It can be seen that the thicker the insulation added, the greater the reduction in both annual required cooling energy and peak cooling load, regardless of the position of thermal insulation. However, the results confirm the “rule of diminishing returns” as the saving declines for every increment in the thickness of the insulation [19].

Changing the thermal capacitance of the external wall has different effects on annual required cooling energy and peak cooling load. It was found that an increase in thermal capacitance is beneficial to the reduction of peak cooling load. The load is reduced by 1.8% by moving the insulation from inside to the outside of the external walls, regardless of the thickness of the thermal insulation. It was also found that the reduction in peak cooling load, achieved by adding extra thermal mass, does not have a linear relationship with the amount of the thermal mass. A 75 mm thick layer of concrete facing indoors (achieved by moving the insulation from the inner surface to the middle of the external wall) reduces the peak cooling load by 1.6%. On the other hand, a 150 mm thick layer of concrete (achieved by moving the insulation from the middle to the outer surface) only reduces the peak load by a further 0.2% (Fig. 4).

The thickness of the thermal insulation also marginally affects the performance of the thermal mass. The reduction

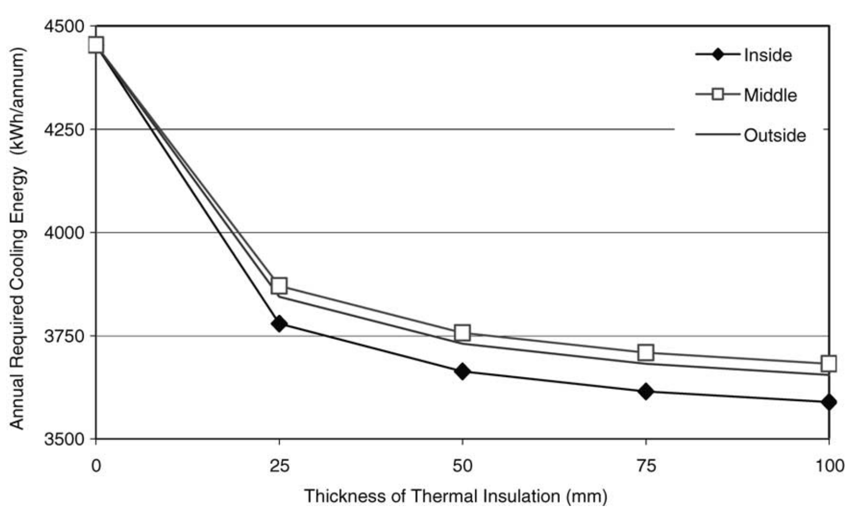

Fig. 3. Effect of increasing levels of insulation in various positions on annual required cooling energy.

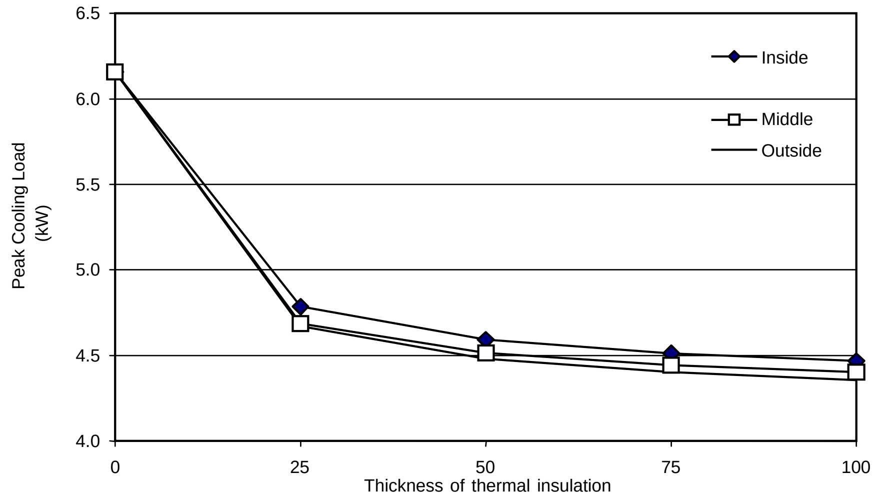

Fig. 4. Effect of increasing levels of insulation in various positions on peak cooling loads.

achieved by the first 75 mm of concrete decreased from 1.6% to 1.1% when the thickness of the insulation increased from 25 mm to 100 mm. By contrast, the reduction achieved by the second 75 mm of concrete increased from 0.2% to 0.7% for the same conditions.

Annual required cooling energy behaves differently to the peak cooling load with respect to an increase in effective thermal capacitance. The maximum saving was achieved when thermal capacitance was minimized, i.e. the insulation was placed on the inner surface of the external wall, regardless of the thickness of the insulation. However, the reduction did not have a linear relationship with the increment in the effective thermal capacitance. The saving from adding thermal insulation in the middle of the external wall was the least in the three scenarios. This finding suggests that adding even more thermal mass may be beneficial to saving energy, but this would exceed the 300 mm limit on wall thickness [18]. The findings described in this section do not agree with those of Bojic et al. [9], and some explanation of this difference is offered in [20].

5.2. Colour of external walls

The solar absorptance of the outside surface of the external walls in the BASECASE model was changed to represent different external finishes. It was found that the annual required cooling energy required has an almost linear relationship to the solar absorptance of the external surfaces, and the lower the solar absorptance, the higher the saving that can be achieved. A 30% reduction in solar absorptance can achieve a 12.6% saving in annual required cooling energy (Fig. 5). The percentage saving in peak cooling load is greater with any change in solar absorptance than the annual required cooling energy.

5.3. Glazing systems

The glazing system used in the BASECASE model was replaced by different glazing systems. The properties of the glazing systems were generated by the computer software WINDOW-5.1 using products from Pilkington^{TM}. It was found that maximum saving in annual required

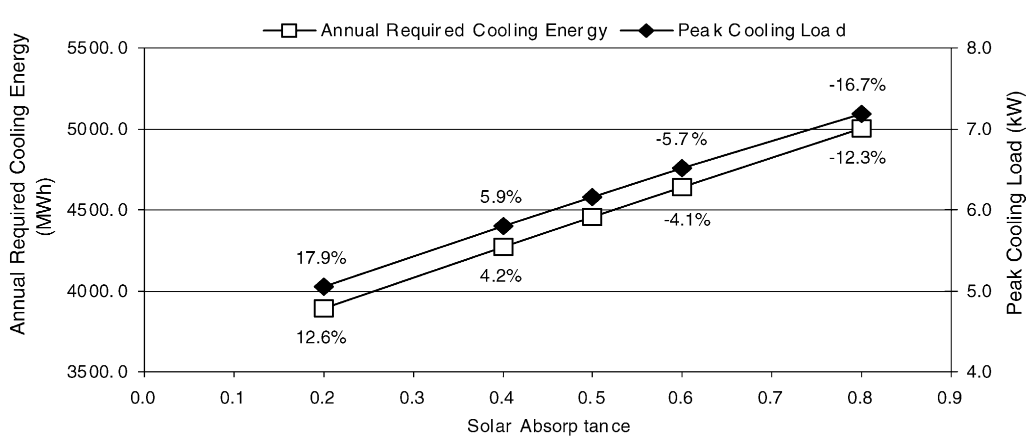

Fig. 5. Annual required cooling energy and peak load for various solar absorptances.

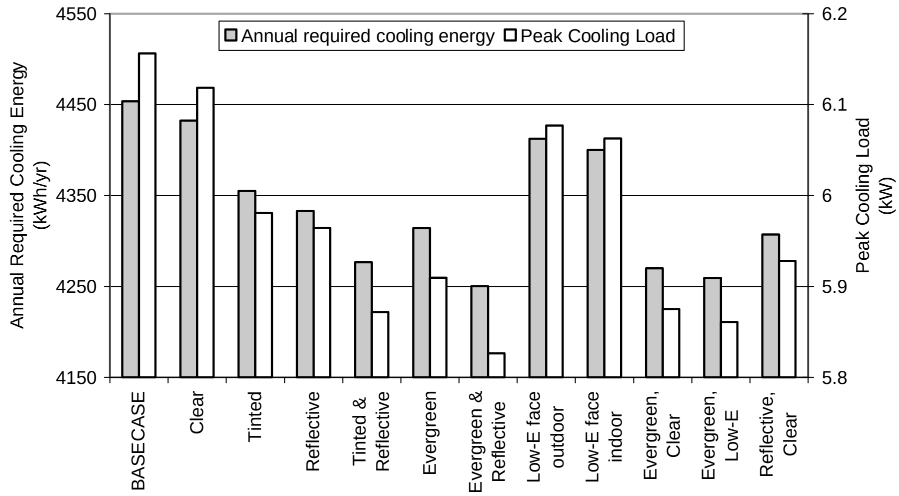

Fig. 6. Annual required cooling energy and peak cooling load for various types of glazing.

cooling energy would be 4.6% by replacing the glazing with a single layer of Evergreen^{TM} glass plus a reflective coating (Fig. 6). The largest reduction in peak cooling load of 5.4% was achieved with the same glazing system.

Most of the single glazing systems have the same *U*-value of 6.9 W/m^2 K, except the two systems using low-E glass. The results of using these six single glazing systems are shown in Fig. 7. It was found that the annual required cooling energy has an almost linear relationship with the shading coefficient of the glazing system. The peak cooling load, however, does not show a linear relationship to an increase in shading coefficient.

It was found that these six glazing systems can be classified in two categories, namely, reflective glass and non-reflective glass (Fig. 8). The reflective glass category has a higher peak cooling load than non-reflective glasses, which have the same shading coefficient. Although the two types of glazing could have the same shading coefficient, the solar energy transferred into the room by both short- and long-wave radiation and convection may have a different impact on the cooling load.

5.4. Window area

The effect of increasing the glazed area in the BASECASE apartment to four times its original size was investigated (Fig. 9). The annual required cooling energy was found to be marginally more sensitive to the change of window area than the peak cooling load. Both loads increased as the window area increased, but the increments are non-linear because the effects are diminishing. This can be explained by the effect of continuous ventilation during the unoccupied hours, which reduces the effect of unwanted solar heat gain by flushing the hot indoor space with cooler ambient air. Large windows, especially unprotected ones, would increase the indoor space temperature to levels higher than the ambient temperature [21].

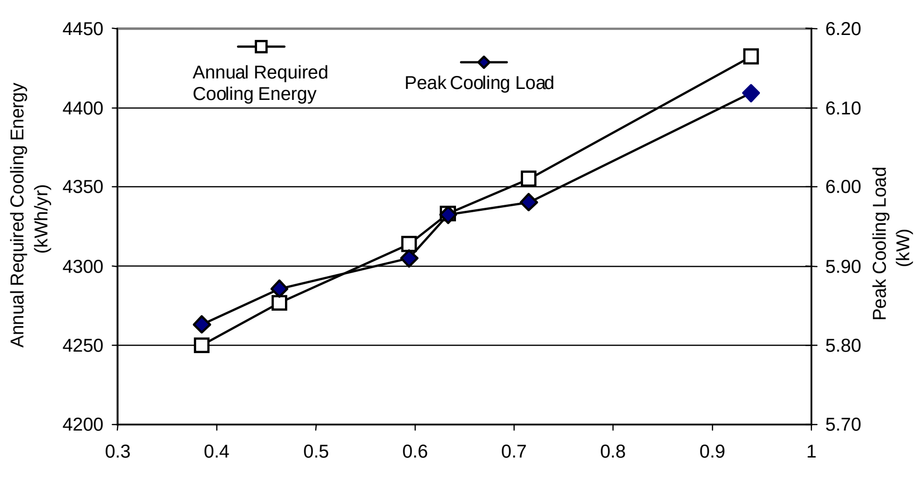

Fig. 7. Effect of shading coefficient on annual required cooling energy and peak load.

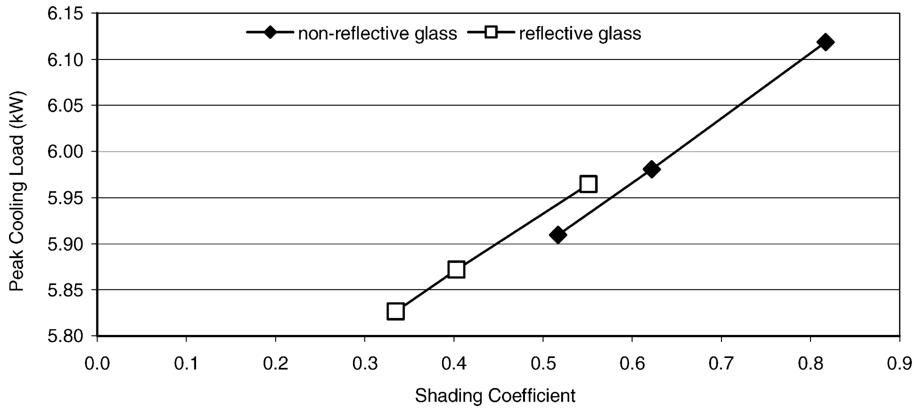

Fig. 8. Comparison between reflective and non-reflective glazing systems.

5.5. Shading

In this research, only fixed external shading devices have been studied. The effects of overhangs and wing walls are studied separately. A maximum length of 1.5 m for both fixed shading devices was used because this is the maximum projection from an external wall that can be exempted from the GFA calculation [22]. The simulation results (Figs. 10 and 11) indicate that the longer the shading, the greater the reductions in both annual required cooling energy and peak cooling load. It can also be seen that peak cooling load is more sensitive to the change in the shading length than annual required cooling energy. The effect of extending the shading quickly diminishes. For example, a 100 kWh/year saving is achieved from the first 500 mm long overhang, while a further saving of only 109 kWh/year is obtained when the overhang is extended by another 1000 mm. This phenomenon is also observed with respect to the peak cooling load.

5.6. Combining the passive thermal design strategies

The findings from investigating the effects of individual strategies have been combined to formulate a building envelope design that has the minimum annual required cooling energy. The most effective combination of strategies has been selected by comparing these results against each other. The maximum savings of annual required cooling energy in comparison to the BASECASE from various strategies are shown in Fig. 12.

It can be seen that the combined effect of insulation and thermal mass achieved the highest saving of almost 20%, followed by a 12.6% saving from using white wall finishes. Cooling load decreases as window area decreases, but because the window area is set at the minimum legal requirement in the BASECASE, no saving can be achieved by further reducing the window area. Using alternative window systems, including shadings, only achieved savings of approximately 5%. However, these last results do not agree with the literature [3]. It is generally believed that a window is the major source of unwanted heat gain in an air-conditioned building. This is because windows usually allow a large amount of solar energy to enter the occupied space. This apartment, however, is mainly occupied at night and this significantly reduces the impact of direct solar gain and hence decreases the effectiveness of any strategies using alternative windows and shading. Moreover, the small

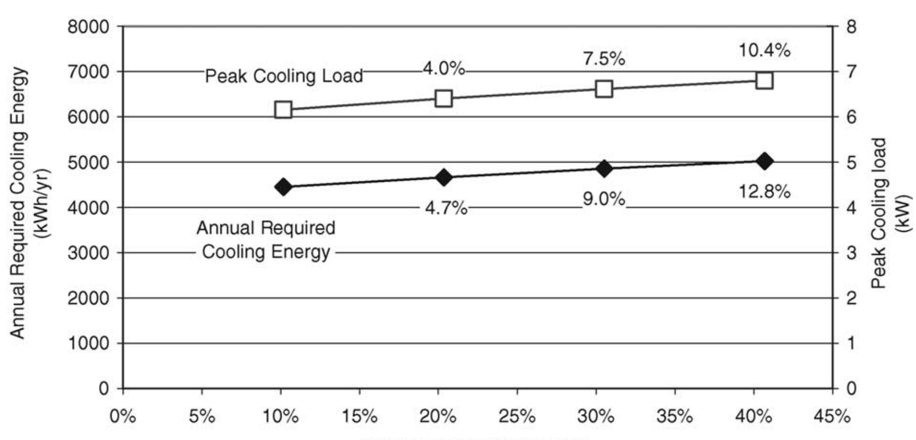

Fig. 9. Effect of change in window-to-floor ratio.

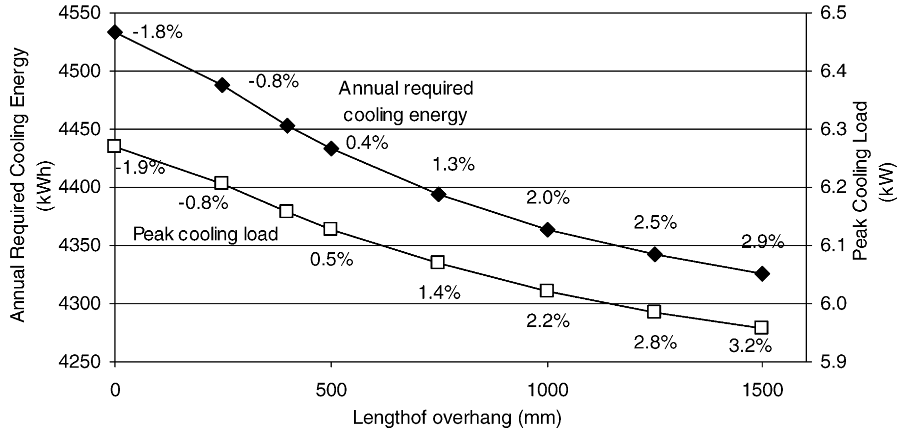

Fig. 10. Effect of length of overhang on annual required cooling energy and peak cooling load.

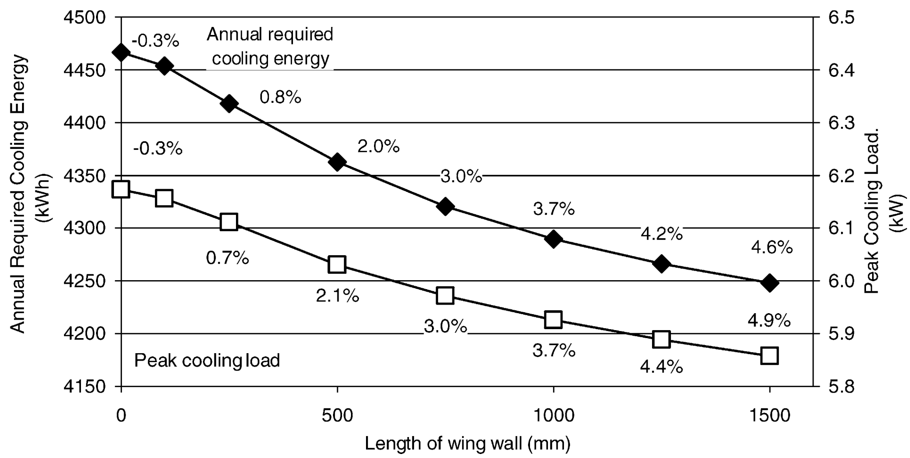

Fig. 11. Effect of length of wing walls on annual required cooling energy and peak cooling load.

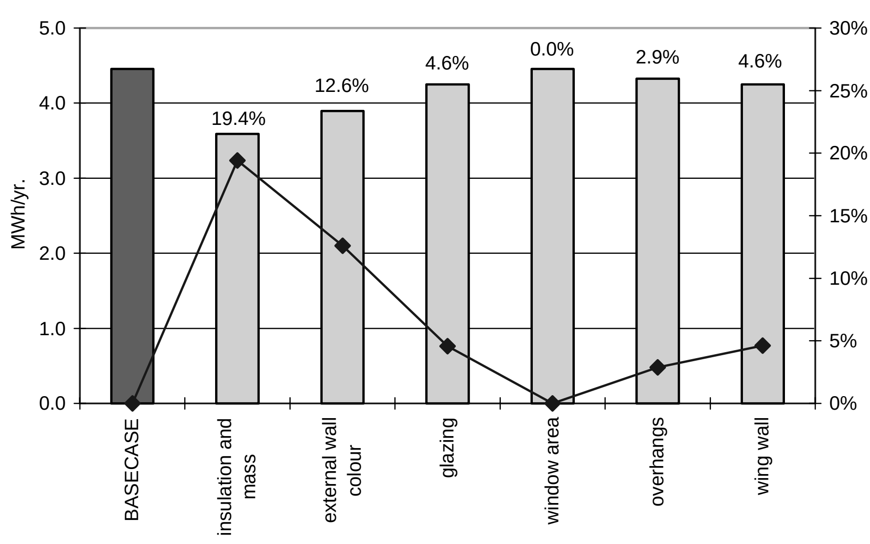

Fig. 12. Energy saving from various strategies.

Table 3
Effect of combined strategies on the annual required cooling energy of individual rooms in the three-bedroom apartment

	Living room		Bedrooms		Study room	
	kWh/m^2	Savings	kWh/m^2	Savings	kWh/m^2	Savings
BASECASE	63.8	–	137.5	–	159.8	–
Combined strategies	50.9	20.2%	86.2	37.3%	106.3	33.5%

Table 4
Effect of combined strategies on peak cooling load of individual rooms in the three-bedroom apartment

	Living room		Bedrooms		Study room	
	W/m^2	Savings	W/m^2	Savings	W/m^2	Savings
BASECASE	152.0	–	195.6	–	221.4	–
Combined strategies	117.6	22.6%	111.0	43.2%	123.0	44.4%

window area in the apartment also reduced the impact of enhanced window designs. Therefore, the results are considered to be credible.

After reviewing the effect of individual strategies, the following combination of strategies was selected:

- Introducing 100 mm thick EPS insulation to the inner surface of external walls
- Changing the external wall colour to white with a solar absorptance of 0.2
- Replacing the glazing with 6 mm thick Evergreen™ glass with reflective coating
- Introducing 1500 mm long overhang and wing wall to all windows

It was found that by modifying the building envelope with the above strategies, the annual required cooling energy (sensible) for the whole flat reduced from 4454 kWh to 3056 kWh, i.e. a saving of 31.4%. The peak cooling load also reduced significantly from 6.2 kW down to 3.9 kW, i.e. 36.8% reduction. The simulation results are shown in Tables 3–5.

When considering the impact of the combined strategies on the individual spaces, it was found that the least saving was achieved in the living room. The bedrooms have the highest reduction in both the annual required cooling energy and peak load (Tables 3 and 4). This may have been caused by the differences in the external wall-to-floor area ratio. Since the strategies are intended to improve the performance of the building envelope, the higher the external wall to floor area ratio, the greater the saving in annual required cooling energy is likely to be. Even though the study room has the same operational parameters as the bedrooms, the relatively smaller external wall area means that it is less affected by the modifications.

The living room has an external wall-to-floor area ratio of only 0.65, which is only approximately one-third of the value of 1.92 for the two bedrooms. The late afternoon/early evening occupancy schedule can increase the benefits from shading and window design strategies, when compared to the late night schedule of the bedrooms. However, those strategies mainly improve the initial conditions of the occupied hours and the temperature of the internal concrete partitions, where the application of thermal insulation on the inner surface significantly reduced the heat stored within the structure. The comparatively higher internal loads also reduced the importance of the skin load and hence reduced the effectiveness of the applied strategies.

When considering a typical floor of an entire block, consisting of all eight flats, the reduction in annual required cooling energy ranged from 26.9% to 27.9% (Table 5), depending on building orientation. The saving in required sensible cooling energy of the typical floor is less than the BASECASE flat because the strategies are less effective at other orientations.

Fig. 13 shows that west-facing flats (as shown by the last three columns for each flat) have the highest reduction in annual required cooling energy. It can also been seen that the application of the combined strategies can effectively even

Table 5
Savings in annual required cooling energy from combined strategies on a typical floor facing various orientations

Building orientation	BASECASE annual required cooling energy (kWh/year)	Combined strategies annual required cooling energy (kWh/year)	Energy savings (%)
As Fig. 1 (north up)	30537	22328	26.9
45° clockwise	30940	22306	27.9
90° clockwise	30721	22342	27.3
45° anti-clockwise	30895	22304	27.8

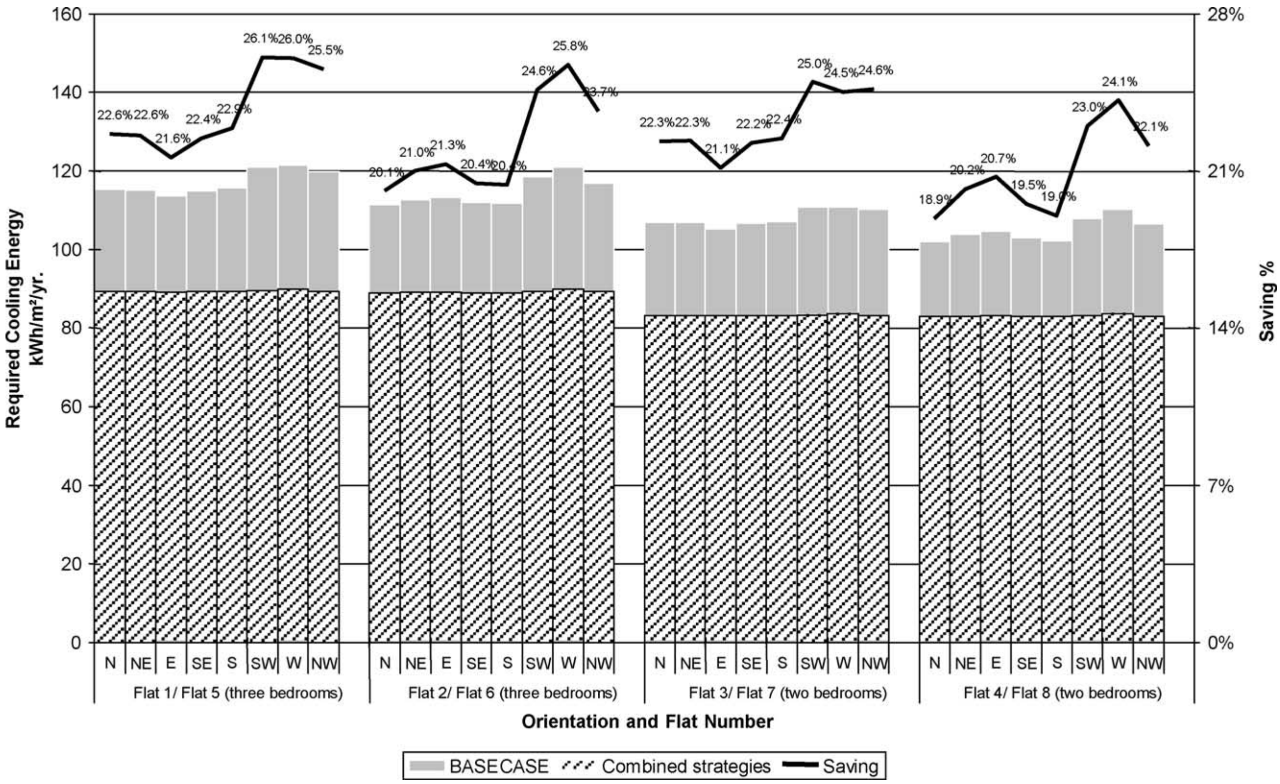

Fig. 13. Comparison of annual required cooling energy per net conditioned floor area for BASECASE and combined strategies for all flats for various orientations.

out the cooling energy requirement of flats facing various orientations.

6. Conclusions

In the context of Hong Kong, this paper has examined six strategies for lowering the energy consumption of high-rise apartment buildings. The results suggest that energy savings for high-rise apartments in hot and humid climate can be as great as other climates. The simulation results for the six passive design strategies indicate that for a predominantly night-occupied apartment, the strategies on improving the thermal performance of external wall are more effective than those for windows. The results show that a saving of 31.4% in annual required cooling energy and 36.8% in peak cooling load for the BASECASE apartment can be achieved.

The simulation results also indicated that there is a large potential to significantly reduce cooling energy consumption with readily available technologies under the current building regulations without sacrificing the spatial efficiency of the design. Some strategies described in this paper can be applied to building design by architects and building designers with minimal cost implication, i.e. the selection of light-colour external wall finish.

This study also suggested that the use of thermal modelling in building design can assist the architect to produce a more energy-efficient design by evaluating the effectiveness of various alternatives. The results of this paper can be integrated with life cycle cost/energy analysis to produce a more holistic picture of environmental impacts and cost benefits of low-energy apartment design.

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